20 kG, 10-FEET LONG SUPERCONDUCTING PROTOTYPE TRANSPORT DIPOLE

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Introduction

Following the successful operation of a 30-inch long 20 kG transport dipole model,[1] it was decided to construct a full size prototype of a 20 kG cold-iron D.C. transport dipole. The general design requirements are shown in Table I.

Table I

General Design Requirements

Clear aperture:	2-inch full gap x 5.25-inch full width x 120-inch long
Mid-plane field:	20 kG
Mid-plane field uniformity:	±0.1% over 4-inch full width at 20 kG
Magnet charge time:	5 minutes or less

Detailed Design

With a design field of 20 kG, a picture-frame iron design was chosen to reduce the excitation required and keep the cryostat relatively compact. To further decrease the ampere-turns required it was decided to refrigerate the iron to 4.2° K. With the iron cold it could be used to support the electromagnetic forces just as in a conventional magnet. As the magnet was intended for only D.C. operation the iron was not laminated. The coil and iron cross-section geometries were chosen to meet the uniformity requirements using computer codes TRIM and LINDA. A 9°-45° double bevel was chosen for the iron ends to make the effective length ($\int Bdl/B_o$) independent of field. An iron length of 10 feet was chosen as being sufficiently long to discover any coil winding or cryogenic problems but which would remain convenient to handle in the laboratory. Vertical holes 0.375-inch diameter were provided at 6-inch intervals along the iron in the coil region to improve liquid helium circulation. These holes had no effect on the field in the useful aperture.

In order to reduce the heat load to the 4.2° K system a relatively low operating current of 200 A was chosen. With the 115,000 amp turns required this choice gave an inductance of 3 H. This was sufficiently low to allow the charging time requirement to be met with a 10-volt power supply. To insure reliable operation it was decided that the coil be fully stable[2] and that the operating current be about 1/3 of the short sample current at 20 kG. The properties of the conductor which was chosen are listed in Table II. As additional passive protection in the unlikely event of a quench a shorted copper turn encircled each of the iron return legs. The turn had a time constant of approximately one second. The iron and coil are shown in Fig. 1.

In order to provide good liquid helium penetration into the winding, epoxy-fiberglass (G-10) spacers were used. These spacers transmitted the electromagnetic forces to the iron yoke. Their separation was chosen to limit the deflection of an individual wire. The coil construction is shown in Fig. 2. Current leads cooled by the helium boil-off gas were used.

Table II

Properties of Conductor

Vendor:	Cryomagnetics, Inc.
Type:	Nb-Ti multifilament composite
Diameter:	.050 inch (0.127 cm)
Copper to superconductor area ratio:	4.25:1
Number of strands:	88
Strand size:	2.3×10^{-3} inches (59μm)
Twist pitch:	0.5 inch (1 cm)
Insulation:	Heavy Formvar
Short sample current:	750 A at 20 kG
Fully stable current:	300 A
Operating current:	215 A
Operating current density:	109 kA/inches^2 (17 kA/cm^2)

The cryostat was designed to provide large liquid helium volume above the coil and still keep the vessel as compact as possible. Since the magnet iron was of rectangular section rectangular cryostat vessels were chosen. The cryostat is shown in Fig. 3. The helium chamber had approximately 350 liters of liquid above the top of the iron. It was made of 304 stainless steel. The use of a liquid nitrogen-cooled radiation shield was dictated to reduce the heat leak to the helium bath. This shield would also intercept conduction heat paths. Aluminum was chosen for the shield. Internal liquid nitrogen storage of 80 liters was provided. The aluminum vacuum vessel was top flanged to facilitate assembly. The rectangular beam pipe, 2 x 5.25 inches inside, was of stainless and insulated from the helium chamber by 0.25 inch of vacuum and aluminized Mylar multi-layer insulation. The weight of the magnet and helium vessel was about 5 tons and was supported by two, 0.5-inch diameter 6AL4V titanium rods in tension. The helium vessel and nitrogen shield were hung from the top lid of the vacuum box by these rods. Pressure relief valves were provided on both helium and vacuum vessels. Many copper/constantan thermocouples were installed on the radiation shield and magnet to aid in the cool down and to provide data for heat leak analysis.

Fabrication

The winding of approximately 12,000 feet of superconductor on the coil form took 10 days. The coil was wound in a two-dimensional race track and the ends bent by hand after assembly into the iron. The helium box, fabricated as two channels with flat ends, was assembled around the magnet and closure welds made. The nitrogen shield was assembled with screws and the entire assembly, hanging from the vacuum box lid, lowered into the vacuum box.

Operation and Testing

The first cool down of the magnet was started July 31,

1970. Because of the large cold mass, the helium chamber was initially filled with liquid nitrogen and allowed to soak for several days. When the nitrogen had completely boiled off, liquid helium from a storage dewar was introduced. The liquid was put in at the chimney end, with the cold gas taken out at the other end to provide uniform longitudinal cooling. Cool down from 77° K took 26 hours and approximately 650 liters of liquid helium. An additional 400 liters filled the helium vessel.

With cryogenic equilibrium established the helium boil off was approximately 4.1 liters/hour. The insulating vacuum remained below 1.0 mtorr.

The magnet was cooled down three times over a six-month period and was held at 4.2° K for about 30 days in total. The cool downs were essentially identical and the steady-state cryogenic performance was unchanged.

The power supply circuit for the magnet is shown in Fig. 4. The stainless steel dump resistor, by virtue of the diode, is in the circuit only when the magnet is discharging. The usual mode of charging the magnet is to set the power supply voltage and current and close the D.C. switch. The supply will maintain a constant voltage until the set current is reached, at which point the voltage drops to a small value as the supply switches to current control mode. The magnet operated initially without incident to design field of 20 kG at 215 A and later the same day to 25 kG at 280 A. The measured stored energy at 20 kG was 72 kJ. Because the coil is fully stable and well cooled the magnet could be charged quite fast without quenching. It was charged to 25 kG in 75 seconds (333 G/sec) and was charged to 9.5 kG in 7.5 sec (1267 G/sec). Power supply voltage limitations precluded faster charge rates. The helium boil-off increases substantially with the charge rate due primarily to magnetization losses in the superconductor. A charge rate of 300 G/sec was observed to increase the loss rate by about 20 liters/hour over the steady-state rate. For a charge at this rate to 20 kG a total of about 370 cm^3 of helium was boiled away.

Magnetic field uniformity measurements were made at 10 kG and 20 kG with a Hall-effect gaussmeter. The field on the mid-plane two inches from the center was higher than the central field by 0.25%, the calculations had predicted the field to be 0.10% high at this point. This discrepancy is due primarily to the welded seam on the beam tube which occurs on the mid-plane. This seam was discovered to be magnetic (measured permeability between 1.5 and 2.0) as a result of the welding thermal cycle. The B-H curve of iron at 4.2^{o} K is known[3] to be somewhat different from the room temperature curve. Any effects on the uniformity from this difference were masked however by the effects of the magnetic weld.

During the lifetime of the magnet it was never quenched. It would probably have quenched at about 28 kG.

Summary

The construction and successful operation of this prototype transport dipole revealed that no inherent difficulties could be expected in production models. A conservative choice of current density and use of a fully stable coil geometry are indicated for reliable, quench-free operation. A compact rectangular cryostat was shown to have low heat leak at modest cost. Further refinement of the design will yield a superconducting transport dipole at a cost per unit length comparable to conventional elements.

References

[1] *Particle Accelerators*, 1, 265 (1970) and NAL TM-211 (1970).

[2] NAL TM-367 (1972).

[3] McInturff and Claus, BNL Internal Report AADD-162 (1970).

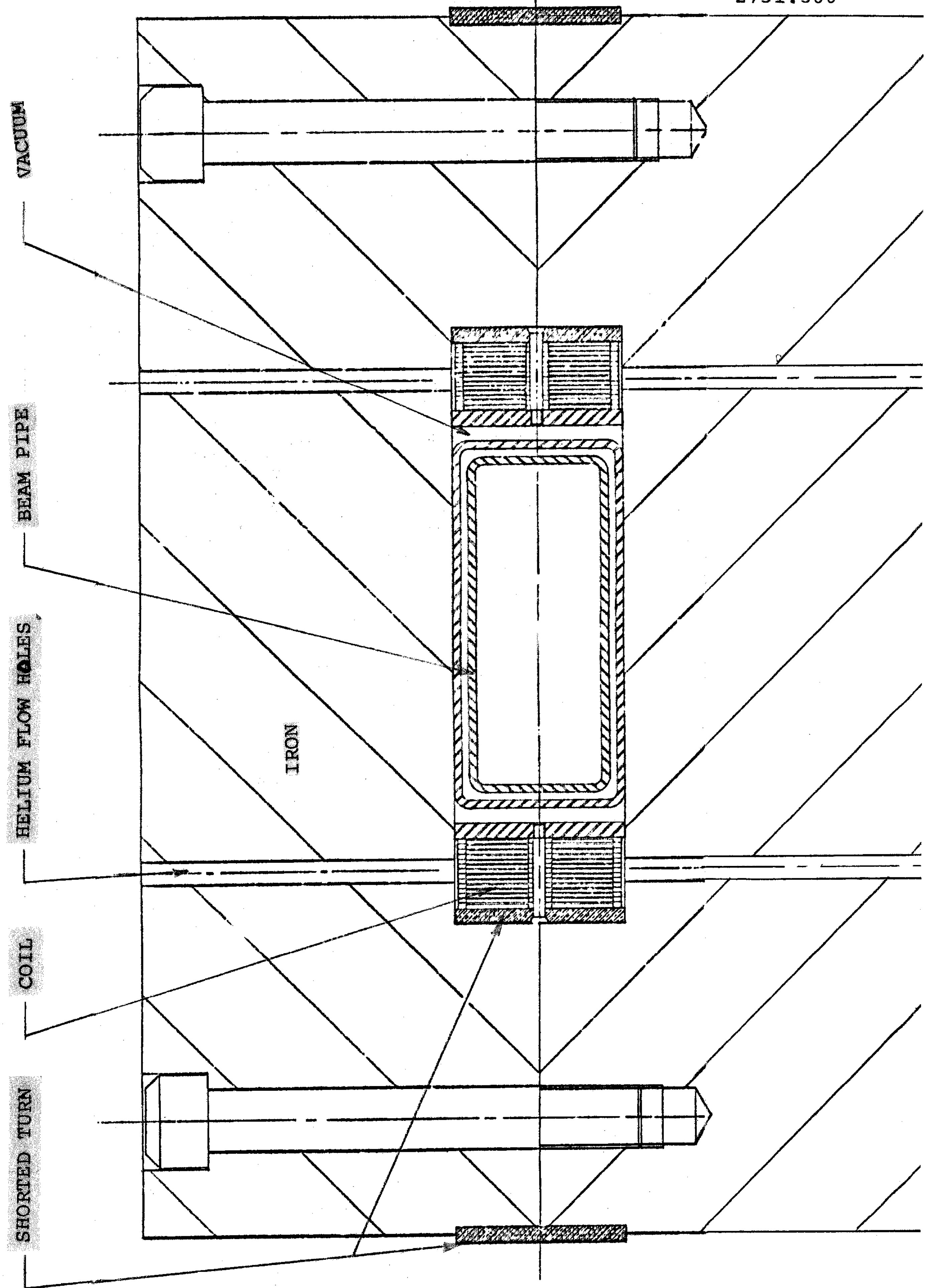


Fig 1

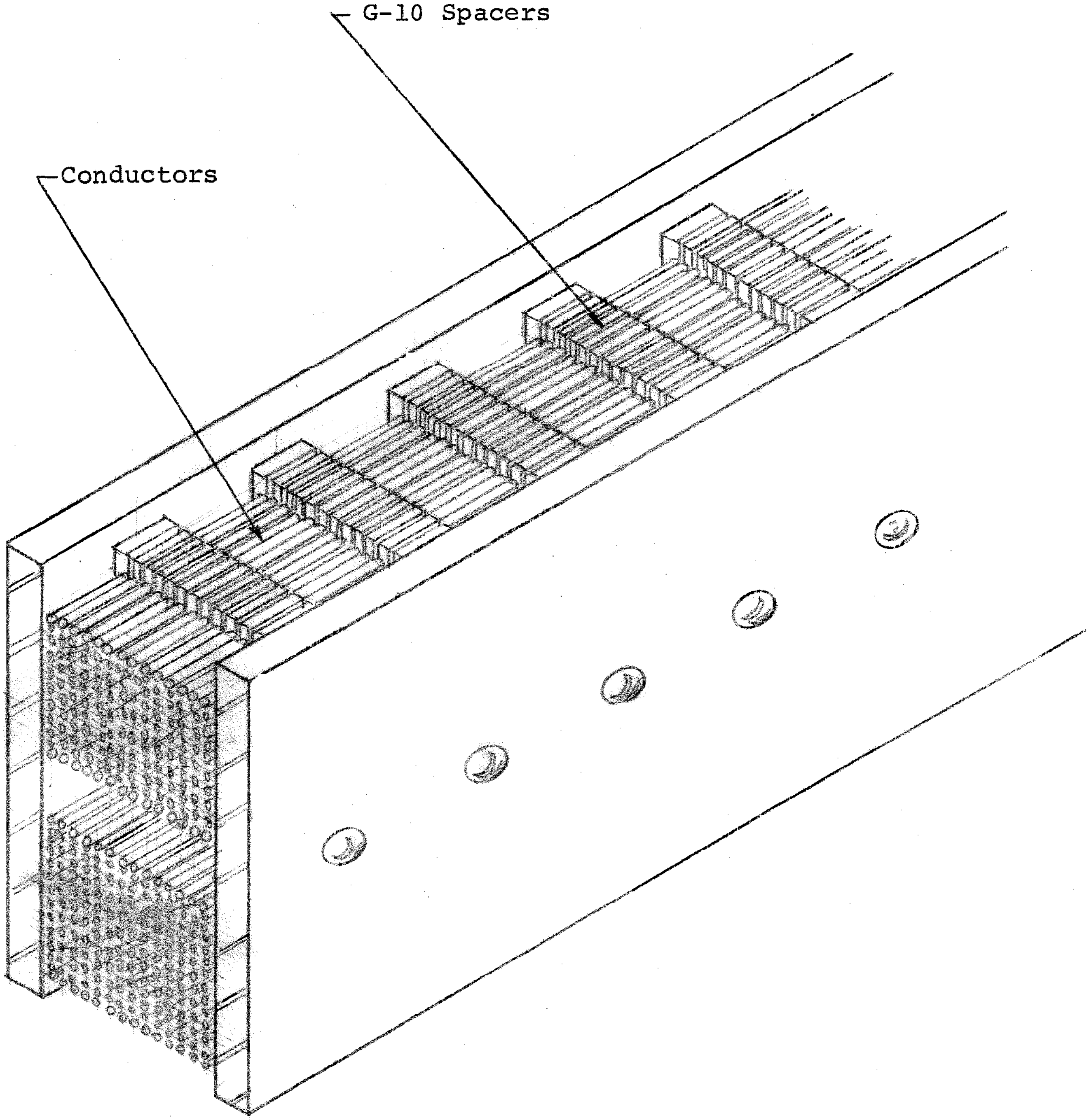


Fig 2

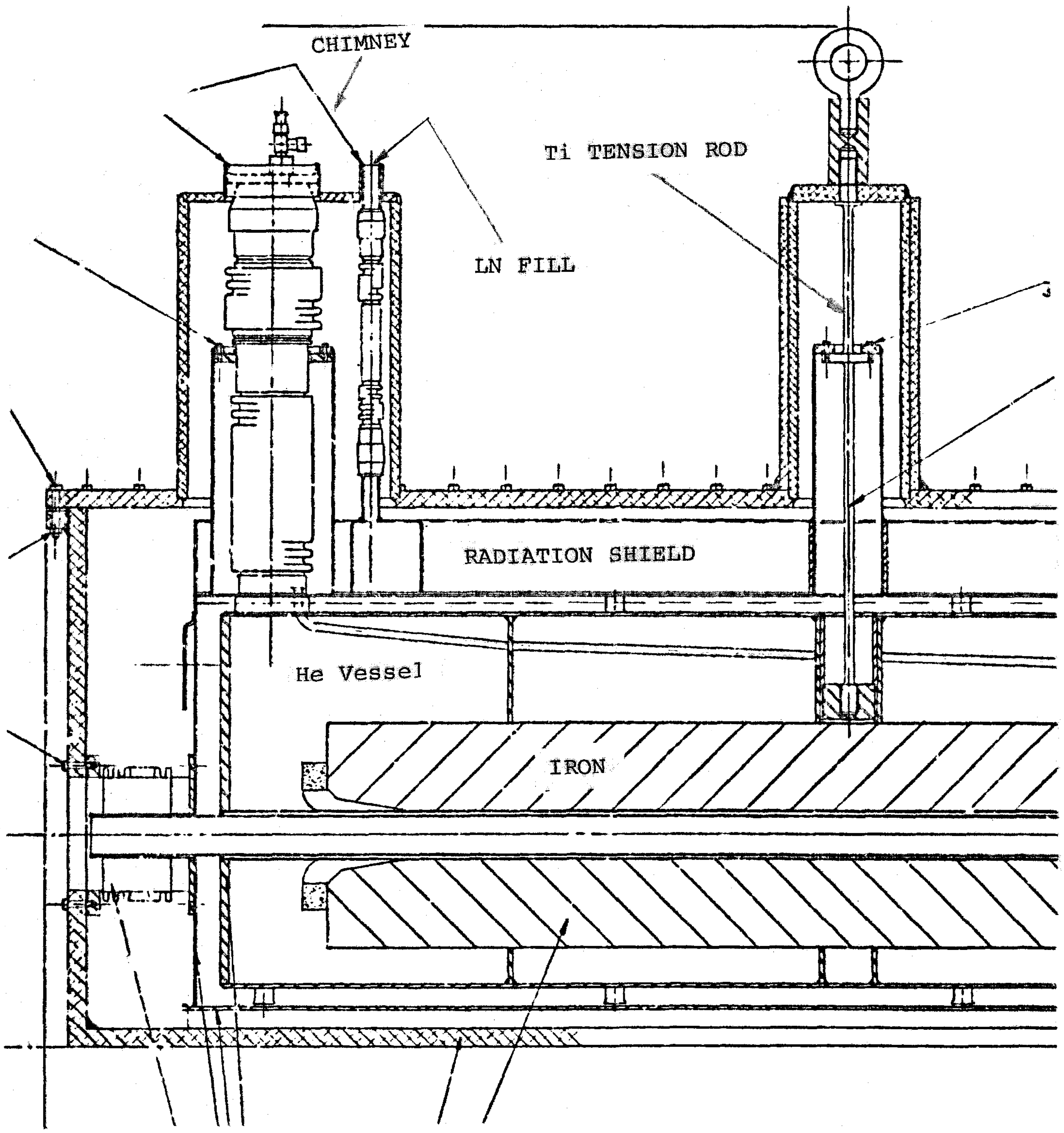
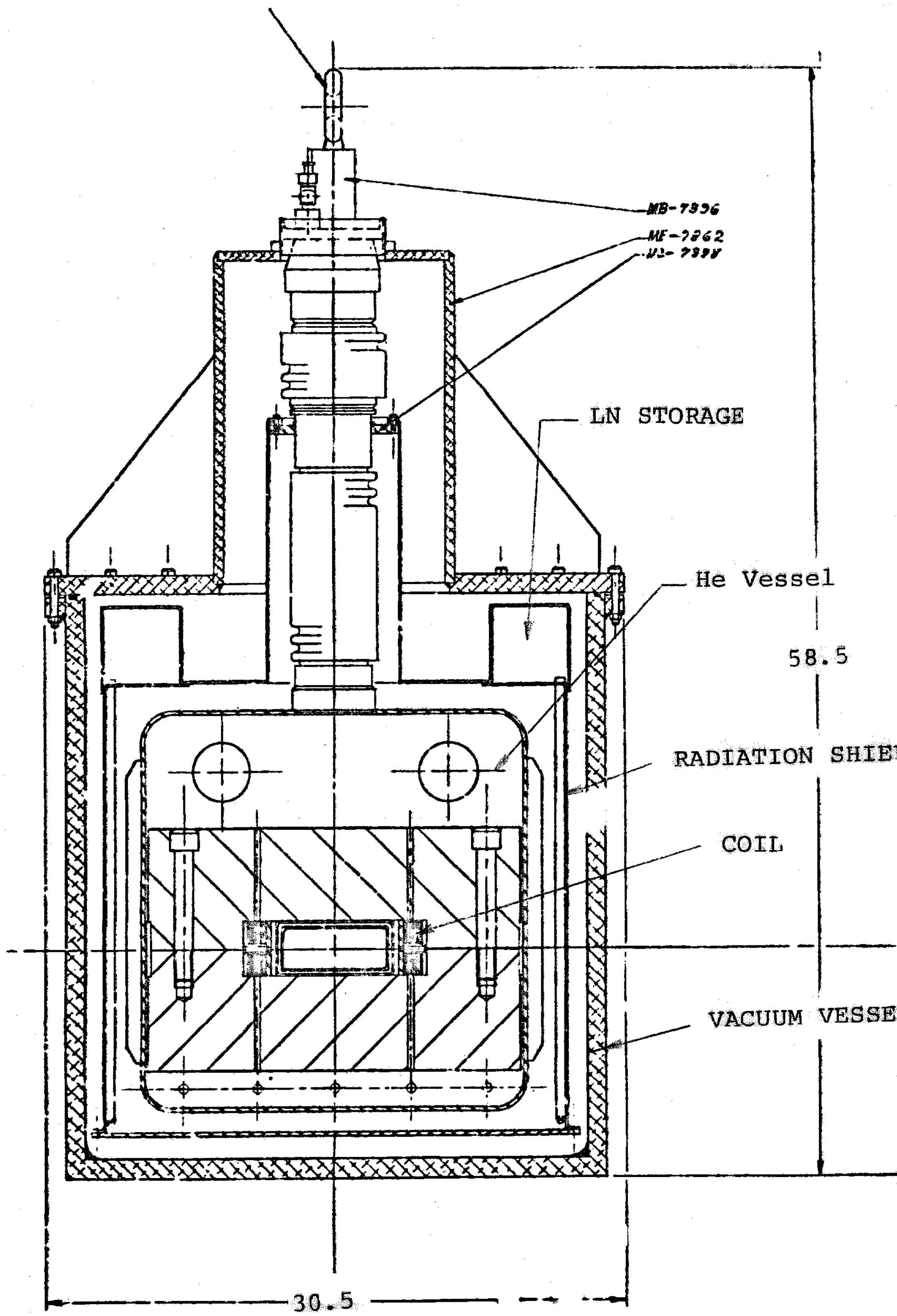

CHIMNEY
Ti TENSION ROD
LN FILL
RADIATION SHIELD
He Vessel
IRON

Fig 3a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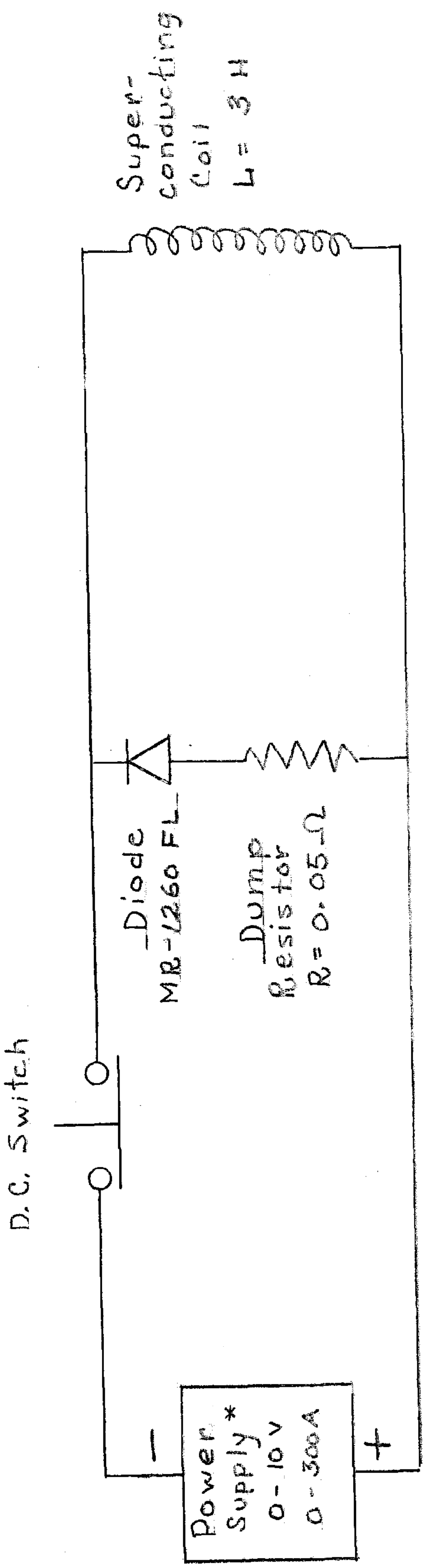
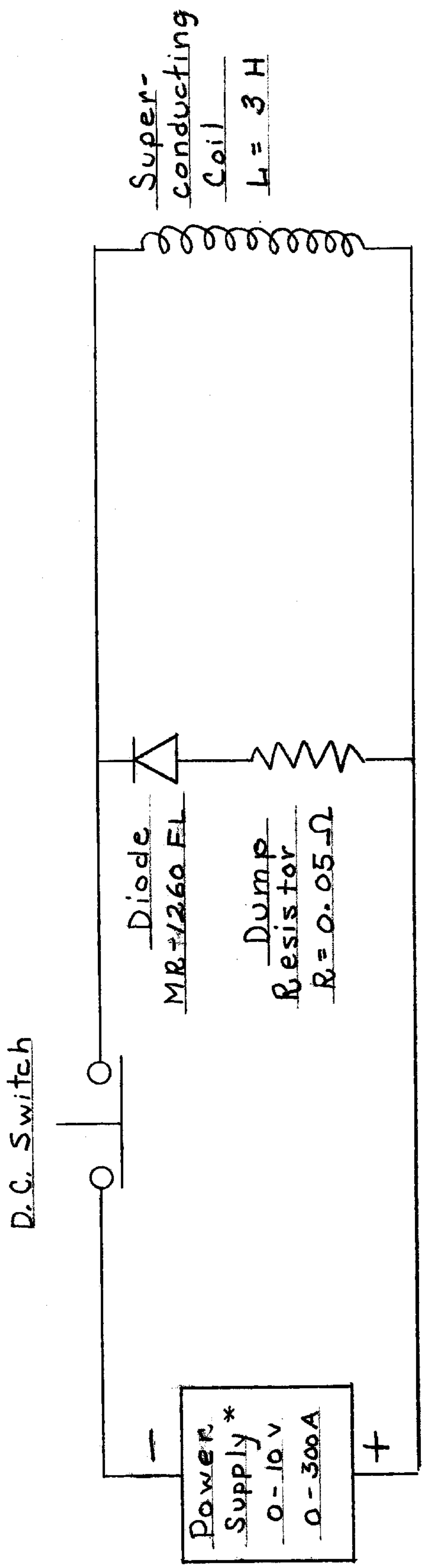
MF-7262
LN STORAGE
He Vessel
58.5
RADIATION SHIELD
COIL
VACUUM VESSEL
30.5

Fig 3b



* Three Hewlett-Packard 6260A in auto parallel

Fig 4



* Three Hewlett-Packard 6260 A in auto-parallel

Fig 4